A stable fiber-based Fabry-Perot cavity

T. Steinmetz,[1] A. Balocchi,[2] Y. Colombe,[1] D. Hunger,[1]
T. W. Hänsch,[1] R. J. Warburton,[2] and J. Reichel[3]

[1] *Department für Physik, Ludwig-Maximilians-Universität, Schellingstrasse 4/III, 80799 München, Germany*

[2] *School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK*

[3] *Laboratoire Kastler Brossel de l'E.N.S., 24 rue Lhomond, 75231 Paris Cedex 05, France*

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Abstract

We report the development of a fiber-based, tunable optical cavity with open access. The cavity is of the Fabry-Perot type and is formed with miniature spherical mirrors positioned on the end of single- or multi-mode optical fibers by a transfer technique which involves lifting a high-quality mirror from a smooth convex substrate, either a ball lens or micro-lens. The cavities typically have a finesse of $\sim 1,000$ and a mode volume of 600 μm^3. We demonstrate the detection of small ensembles of cold Rb atoms guided through such a cavity on an atom chip.

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An optical cavity amplifies the interaction between light and matter by recirculation of the light at a resonant frequency. This feature is exploited in a number of fields, notably lasers and optical sensors. Furthermore, it is crucial to experiments and possible technologies based on exploiting the quantum mechanical properties of individual atoms and photons. In this field of cavity quantum electrodynamics (CQED), the crucial features of the cavity are a small mode waist and/or mode volume V_m, and a high finesse $\mathcal{F} = \Delta\nu/\delta\nu$ (where $\Delta\nu$ is the free spectral range and $\delta\nu$ the linewidth of the cavity), equivalently a high Q factor $Q = \nu/\delta\nu$ [1]. The "gold standard" for CQED cavities is still being set by macroscopic Fabry-Perot (FP) cavities with superpolished, concave mirrors. These mirrors have relatively large radii of curvature ($R = 20\,\mathrm{cm}$ is typical) and achieve record finesse values of $\mathcal{F} > 2 \times 10^6$ [2]. However, there are situations where cavities of this type cannot be used, and a number of alternative cavity designs have been proposed (see for example [3]). A notable example calling for an alternative cavity design is single-atom detection for quantum information processing on atom chips [4, 5, 6, 7] where the macroscopic cavity is incompatible with the microscopic chip. Another example concerns the insertion of quantum objects such as quantum dots and molecules into cavities where the need for cryogenic temperatures makes a macroscopic design problematic. While microscopic cavities are being actively developed, existing designs typically lack an easy way of tuning the cavity into resonance.

An optical fiber-based resonator offers an attractive way forward [7, 8]. Here we describe a fiber-coupled Fabry-Perot (FFP) cavity that employs concave dielectric mirror coatings with small radius of curvature, realized on the fiber tip. A stable cavity is constructed as shown in Fig. 1(a),(b), either from one such fiber tip facing a planar mirror ("1FFP"), or from two closely spaced fiber tips placed face-to-face ("2FFP"). Thus, unlike the design of [8], the cavity can easily be used in transmission, and does not require a concave depression to be fabricated on the substrate. We demonstrate how such cavities can be easily fabricated using commercially available lift-off coatings. Tunability is achieved by attaching one of the fibers to a piezoelectric actuator. Because of the small fiber diameter (125 μm), very short cavities ($< 10\lambda/2$) can be realized even with radii of curvature $R \leq 1\,\mathrm{mm}$, still leaving a sufficiently large gap to introduce cold atoms. We achieve stable cavity modes with a finesse of $\sim 1,000$ in the near infrared. The mode volume is $V_m = 600\,\mu\mathrm{m}^3$, to be compared to $V_m = 1680\,\mu\mathrm{m}^3$ for the smallest-volume macroscopic FP cavity that has been used with atoms [9]. In terms of CQED parameters, the small mode volume results in an exceptionally high coherent atom-photon coupling rate, $g_0/2\pi = 180\,\mathrm{MHz}$ (calculated for the Rb D2 line at $\lambda = 780\,\mathrm{nm}$) . Therefore, in spite of the comparatively high damping rate,

$\kappa/2\pi = 2.65\,\mathrm{GHz}$ which results from the moderate finesse and short length, the cavity reaches a single-atom cooperativity parameter greater than unity, $C = g_0^2/2\kappa\gamma = 2.1$ where $\gamma/2\pi = 3\,\mathrm{MHz}$ is the atomic linewidth, signaling the onset of quantum effects such as enhanced spontaneous emission into the cavity mode and a significant modification of cavity transmission by the presence of a single atom. The potential of this approach is demonstrated here with an experiment using a 2FFP cavity to detect an extremely weak flux of cold atoms magnetically guided on an atom chip. We present this technology not only as an important stepping stone towards on-chip single atom detection but also for cavity experiments with quantum dots, semiconductor nanocrystals and molecules, and for telecoms devices.

The concave mirrors are fabricated from a convex template and a lift-off step. For large radii of curvature, ≥ 500 μm, the template is a commercial ball lens whereas for smaller radii, $100 - 500$ μm, the template is a silica micro-lens specially fabricated for these experiments. The micro-lenses are etched into a planar silica substrate following the melting and re-solidification of a photoresist mesa. Surface tension provides an extremely smooth photoresist surface such that the roughness in the micro-lens is determined only by the subsequent dry-etching step and can be as small as ~ 1 nm. The template is coated [14] in one run with a release layer and silica-titania dielectric Bragg stack, with a stopband centered either at 780 nm or 850 nm and nominal reflectivity of 99.7%. We then position a cleaved single mode fiber immediately above the center of the coated lens by maximizing the back reflection of a laser beam coupled into the fiber. The fiber is then glued in place with an UV-curing epoxy, after which the application of a small force is sufficient to detach the mirror from the original substrate. The result is a fiber functionalized with a highly reflecting concave mirror, as shown in Fig. 1(c). A complete 2FFP cavity is shown in Fig. 1(d).

In order to characterize the modes of a 1FFP cavity, we measured the white light transmission spectrum for several values of the cavity length L. We find that stable cavity modes with high $\mathcal{F}$ can be established with little attention to the alignment, unlike the planar-planar cavity geometry which is extremely sensitive to alignment and mechanical noise. The results are shown in Fig. 2(a). As expected for a FP cavity, for each L there is a series of longitudinal modes, until at the smallest L there is just one longitudinal mode in the stopband. Each longitudinal mode consists of a series of finely spaced modes, corresponding to the different transverse modes. This lifting of the degeneracy of the transverse modes allows a spectroscopic determination of the mirror curvature. Fig. 2(b) plots the wavelength shift of the higher order modes relative to the fundamental as a function of L showing how the spacing increases as L decreases. The solid curves in Fig. 2 are

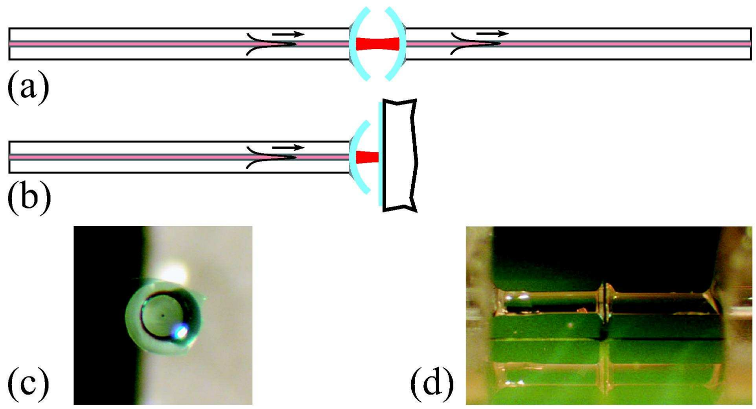

FIG. 1: (a) and (b) Concept of the miniature cavity. The basic building block is an optical fiber functionalized with a concave dielectric mirror. Two such fibers, brought sufficiently close to each other, result in a stable Fabry-Perot cavity which can be interrogated remotely, either in transmission or in reflection, through the two fibers ("2FFP" configuration, (a)). Alternatively, a single fiber can be brought close to a reflecting planar surface ("1FFP" configuration, (b)). The 1FFP configuration is suitable for use with nanofabricated structures such as quantum dots. (c) A single-mode optical fiber, total diameter 125 μm processed with a concave mirror. The mirror has radius 1000 μm with a stopband centered at 780 nm. (d) A miniature cavity, realizing the configuration (a), mounted on an atom chip used in the detection of cold atoms (Fig. 4).

the results from Gaussian optics for a stable, planar-spherical cavity [10], $\Delta\lambda = (\lambda^2/2\pi L)\Delta(m + n)\cos^{-1}\sqrt{1 - L/R}$ where m, n are the lateral mode indices. At large (small) L, the results are best described with a radius of about 200 (230) μm. This compares well with the radius of the micro-lens template, 250 μm. The slight dependence on L is likely to result from a slight "softening" of the mirror away from its center: as L increases, the beam waist at the curved mirror increases, probing more of the curved mirror.

The limited resolution of the spectrometer prohibits a proper measurement of the finesse, and only a lower limit can be deduced ($\mathcal{F} > 500$ for small L). We have therefore measured the cavity transmission as a function of L using grating-stabilized diode lasers (Fig. 3). To determine the finesse, two lasers were simultaneously coupled into the cavity. The first laser is locked to a sub-Doppler line in the ^{87}Rb D2 spectrum at $\lambda = 780.27$ nm, the second is tuned several κ away to 780.6 nm using a wavemeter. The known wavelength difference of the two lasers allows us to calibrate the length scan with a better precision than the length-voltage characteristics of the piezo. Additionally, we simultaneously recorded the transmission of a third diode laser at

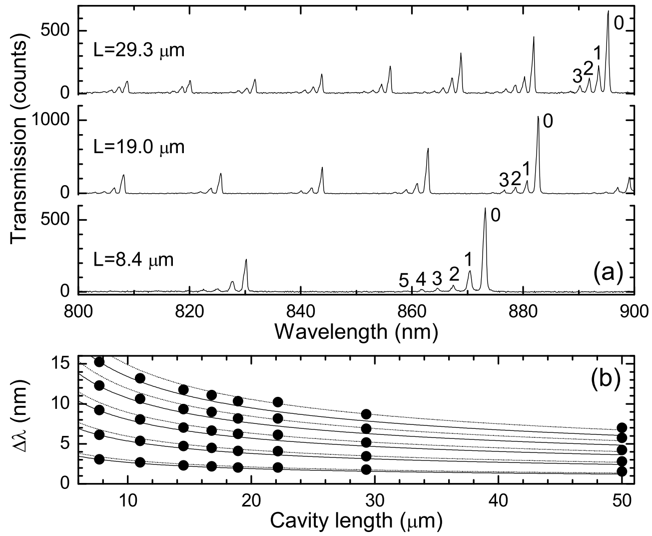

FIG. 2: (a) White light transmission spectra of a 1FFP cavity recorded at three different cavity lengths, L. The mirrors have a stopband centered at 850 nm. L is the effective cavity length, determined by $L = 1/2\Delta(1/\lambda)$ where $\Delta(1/\lambda)$ is the change in wave number from one fundamental longitudinal mode to the next. The modes are labeled with the sum of the two lateral mode indices, m and n. The widths of the transmission peaks are limited by the spectrometer and therefore do not reflect the true finesse. (b) Separation in wavelength of the higher lateral modes from the fundamental mode as a function of L at $\lambda = 850$ nm. The solid (dashed) line represents the analytical result for a spherical-planar FP cavity with radius $R = 230$ (200) μm.

828.25 nm in order to determine unambiguously the absolute cavity length. As a typical result, we have measured a finesse $\mathcal{F} = 1,050$ for a 2FFP cavity with $L = 27\,\mu$m and $R = 1,000\,\mu$m using a single-mode fiber on the input side and a multimode fiber on the output side. This is in good agreement with independent measurements of the mirror transmission, $T = 8 \times 10^{-4}$, and loss, $\ell = 2.4 \times 10^{-3}$ [15]. From these values, the expected finesse is $\mathcal{F} = \pi/(T + \ell) = 980 \pm 40$. This indicates that the finesse of the FFP is as high as the coatings allow. The 1/e beam waist in the cavity in Fig. 3 is $w = 5.4\,\mu$m, implying a cavity mode volume $V_m \sim 600\ \mu$m^3 and $C = 2.1$ for Rb.

We have used the 2FFP cavity as a very sensitive detector for magnetically guided atoms on an atom chip. The experimental setup is similar to our previous experiments [11, 12], but contains

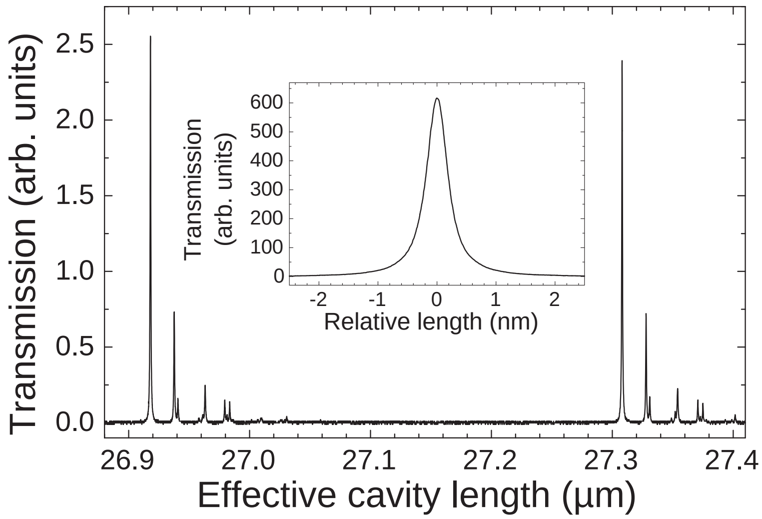

FIG. 3: Transmission of a 2FFP cavity versus cavity length. A piezo is used to vary the cavity length. The absolute length is determined by using up to three lasers as described in the text. The mirrors have radius 1,000 μm with a stopband centered at 780 nm. The cavity has an effective cavity length of 27 μm with a finesse of 1050; equivalently, free spectral range 5500 GHz and mode width (FWHM) 5.29 GHz. The inset shows the line shape of the fundamental (0,0) mode.

an FFP subassembly. Each fiber is glued onto a piezoelectric actuator, and the piezos are glued onto a ceramic bridge while monitoring the cavity transmission signal. The mirror spacing on axis is 27 μm as in Fig. 3, leading to a gap between mirror edges of $\sim 15\,\mu$m; the finesse is 260. The subassembly is glued onto the chip with a 230 μm separation between the cavity axis and the chip surface (Fig. 4 (a)). A magnetically trapped cloud of ^{87}Rb atoms at a temperature of 70 μK is produced in an initial trap and then released into a very elongated Ioffe-Pritchard potential, created using a “Z wire” [4]. This potential guides the atoms through the center of the resonator mode. The cavity mode is excited by a very weak resonant probe laser, both the laser and the mode being tuned to atomic resonance. The transmitted signal is detected with a photon counter. Fig. 4 (b) shows sample transmission signals with and without atoms. We have independently determined the atomic density and temperature before entry into the cavity using absorption imaging and time-of-flight analysis. Integrating the initial density over the cavity mode yields an upper-bound estimate $N_{\rm max}$ for the number of atoms in the cavity mode, $N_{\rm max} \sim 50$. It is clear however that the true number of atoms contributing to the signal is much lower because the transverse size of the atom cloud is significantly larger than the gap between the mirrors, so that a large part of the

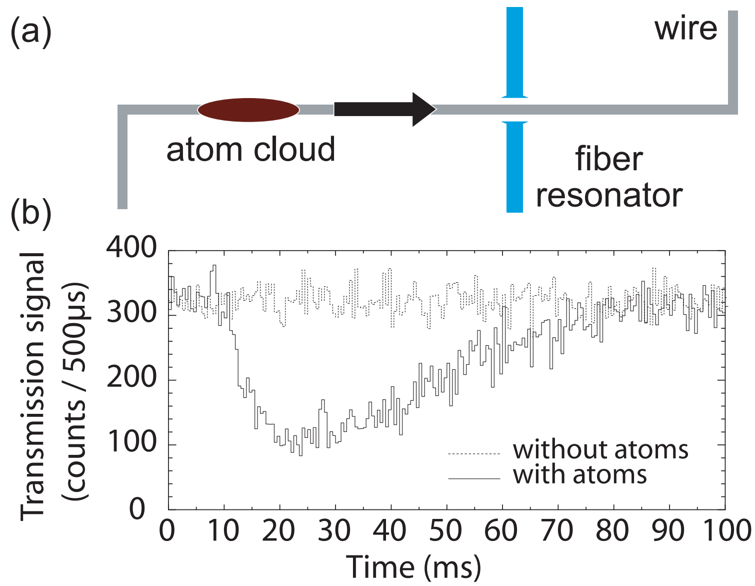

FIG. 4: Atom detection with an on-chip fiber resonator. (a) At $t = 0$, a magnetically trapped atom cloud ($T = 70\,\mu$K) is released into a very elongated Ioffe-Pritchard potential, created using the wire shown in gray. This potential guides the atoms through the center of the resonator mode. (b) Transmission signal of the fiber resonator for a single experimental run (solid line), along with an empty cavity transmission signal (dashed line). The transmission drops to 35% of the empty-resonator value.

atoms is lost upon entering the cavity, and does not contribute to the signal.

Our current cavities aim for high cooperativity. It is interesting however to consider what improvements would be necessary to enter the strong coupling regime of CQED, i.e., $g_0 > \kappa, \gamma$ [1]. To obtain strong coupling, it is preferable to increase the mirror distance L provided $L \ll R$: for a given R, κ drops as $\kappa \propto L^{-1}$, whereas g_0 only decreases as $g_0 \propto L^{-3/4}$. $L = 200\,\mu$m is a realistic value where alignment should still be manageable, and where the spot size on the mirrors remains much smaller than the mirror diameter, so that clipping loss can still be neglected. At this L, the parameters of the 2FFP cavity with $R = 1$ mm would become $g_0/2\pi = 42$ MHz and $\kappa/2\pi = 360$ MHz. Thus, the finesse needs to be improved by roughly a factor of 10, to $\mathcal{F} = 10,000$, in order to reach the strong coupling regime. Presently, the finesse of our cavities is limited by the quality of the multilayer coatings. However, the transfer coating technology continues to improve as suggested by the fact that the transfer coatings used in [8], fabricated after the ones used here, resulted in a measured finesse $\mathcal{F} = 6,000$. Speculating that the coating quality can be improved further, the remaining issue is the surface roughness of the template for the liftoff process. For a ball lens from the batch used in our current cavities, an AFM measurement gave an rms roughness of $\sigma = 1.7\,\text{nm}$. Following a standard estimate for scattering loss, $S = (4\pi\sigma/\lambda)^2$, this roughness must be improved to $\sigma \leq 0.7\,\text{nm}$ which is achievable both with superpolishing and with micro-lens fabrication.

We conclude by noting that, even without any further improvement, the FFP cavities described here should enable single-atom detectivity with good signal-to-noise ratio [6, 7]. Unlike dispersive detection without a resonator [13], this technique will ultimately allow detection with less than one spontaneous emission per atom on average, enabling preparation of single-atom states.

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